Charm in nuclear matter

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Strangeness in Quark Matter
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Generation of Mass

Higgs ➤ Masses of elementary particles: quarks, leptons

Masses of hadrons ➤ dynamically generated in QCD

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Hadron Masses from QCD Sum Rules

correlator $\Pi(q) = \int d^4x\, e^{iqx} \langle \mathrm{T}\left[j(x)j^\dagger(0)\right]\rangle$

hadronic d.o.f.

$\pi \quad \rho \quad \omega \quad J/\psi \quad a_1 \quad D \quad B$

$p \quad n \quad \Delta \quad \Lambda$

phenomenology

Sum ⟷ Rule

quark d.o.f.

$u \quad d \quad s$

$c \quad b$

QCD

dispersion relation $\Pi(q^2) = \frac{1}{\pi}\int_0^\infty ds \frac{\mathrm{Im}\Pi(s)}{s-q^2}$

$$\int_0^\infty ds \frac{\text{spectral density}(s)}{s-q^2} = \Pi_{\mathrm{OPE}}(q^2)$$

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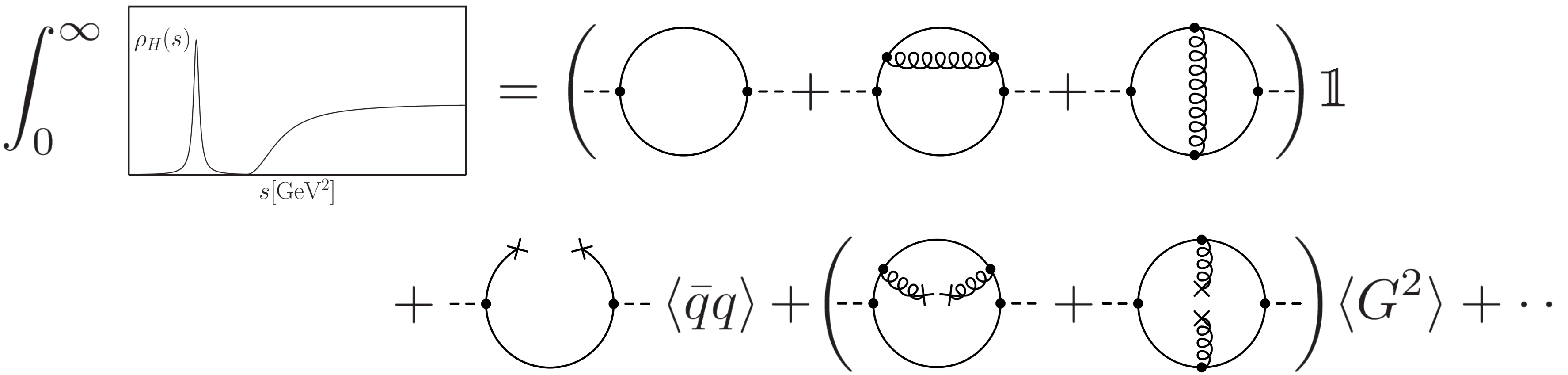
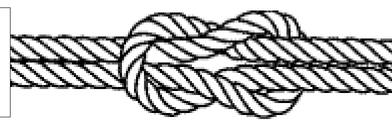
Hadron Masses from QCD Sum Rules



Hadron masses



QCD condensates

Chiral Symmetry Breaking

vacuum – (spontaneous) chiral symmetry breaking:

order parameter $\langle \bar{q}q \rangle \neq 0$

➡ mass splitting of chiral partner mesons

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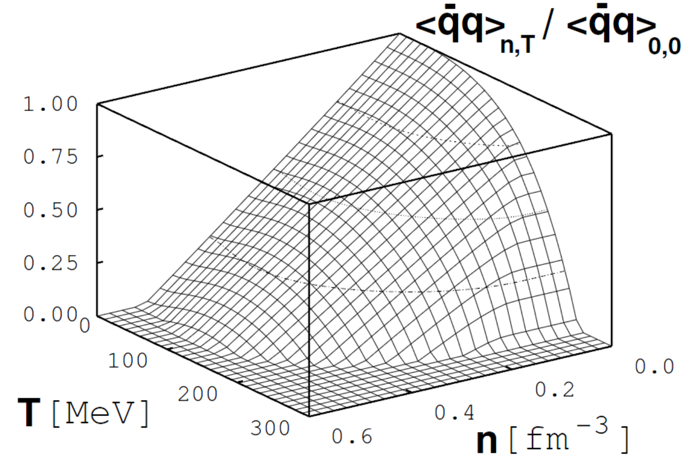
Chiral Symmetry Restoration in Medium

medium modifications:

non-zero temperature (T)
and baryon density (n)

$$\langle\bar{q}q\rangle_{T,n} = \langle\bar{q}q\rangle\left(1 - \frac{T^2}{8f_\pi^2} - \frac{\sigma_N\, n}{m_\pi^2 f_\pi^2} + \cdots\right)$$



[Zschocke et al., Bormio Proc. (2002)]

chiral restoration ➔ $\langle\bar{q}q\rangle_{T,n} \rightarrow 0$

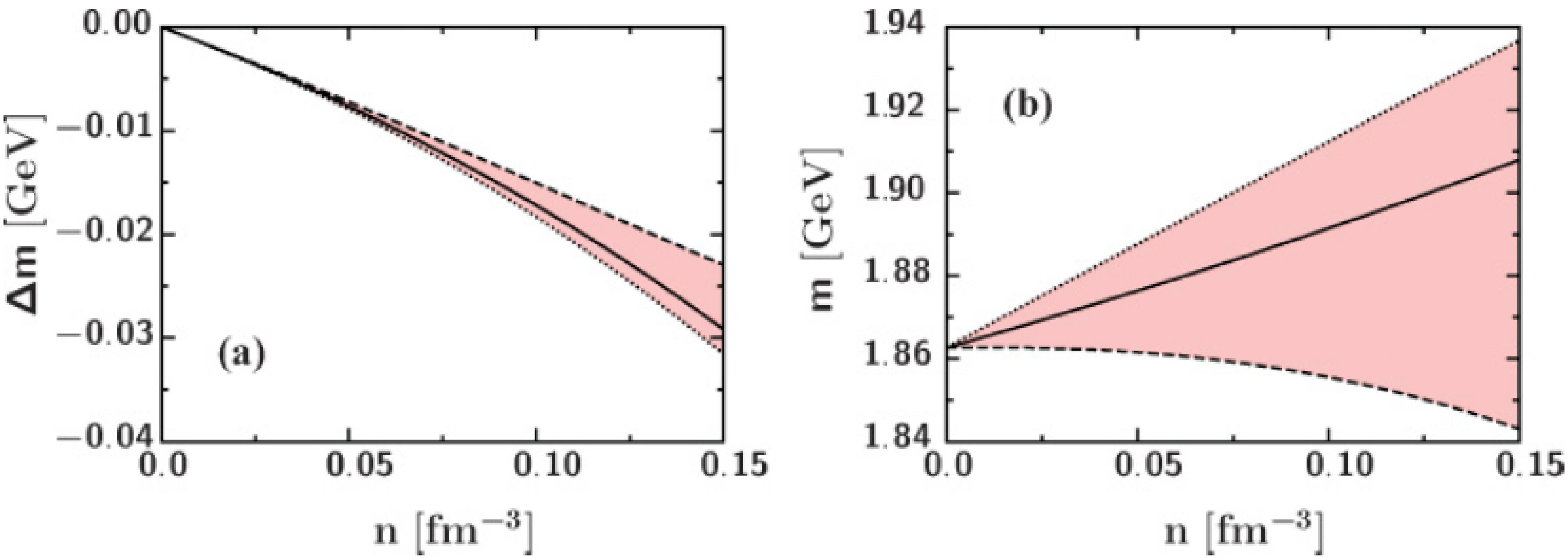
medium modification of mesons – (T, n) effects

changing order parameters of spontaneous chiral symmetry breaking

QCD Sum Rules

Numerical Sum Rule Evaluation: pseudo-scalar D meson

utilizing in-medium OPE up to mass dimension 5 [Hilger et al., PRC 79 (2009)]



Issue associate production of $c\bar{c}$ vs. in-medium masses / mass splitting

➔ $c\bar{c}$ production on shorter time scale than hadronization & charm conservation

➔ D production cross section not much affected

[Andronic et al., PLB 659 (2008)]

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Probing the Chiral Condensate with Open Charm Mesons

light mesons, e. g. ρ

$$\Pi^{(\rho)}_{\mathrm{OPE}}(q) \propto m_q \langle \bar{q} q \rangle$$

- chiral condensate contribution suppressed
- gluon and four-quark condensates important

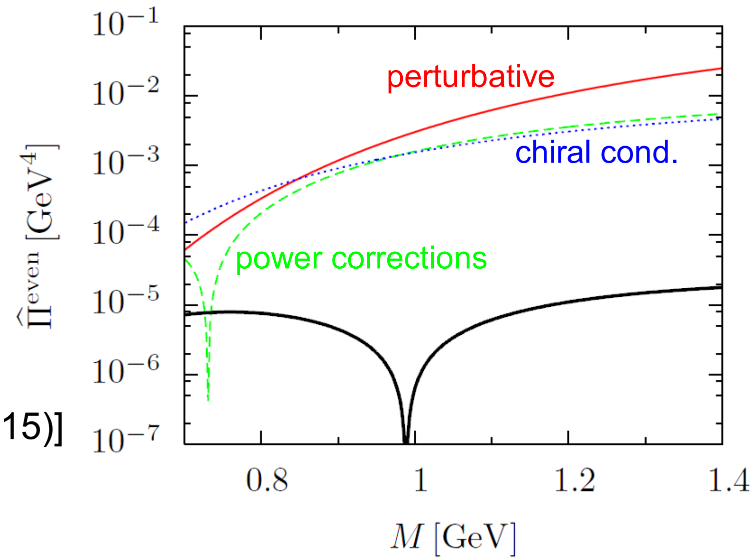
[Rapp et al., Landolt-Börnstein (2010)]

open charm mesons, e.g. D

$$\Pi^{(D)}_{\mathrm{OPE}}(q) \propto m_Q \langle \bar{q} q \rangle$$

chiral condensate contribution dominates

[Hilger et al., PRC 79 (2009)], [Buchheim et al., PRC 91 (2015)]



→ highly sensitive to chiral condensate

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Chirally Odd Condensates – candidates for order parameters

➔ chirally odd condensates: not invariant under chiral transformations

$\varphi \ldots N_f$ vector

$$\varphi = \varphi_{\mathrm{L}} + \varphi_{\mathrm{R}} \,, \qquad \varphi_{\mathrm{L,R}} = P_{\mathrm{L,R}}\varphi = \frac{1}{2}(1 \mp \gamma_5)\varphi$$

chiral transformations

$$\varphi_{\mathrm{L,R}} \longrightarrow e^{-i\Theta^a_{\mathrm{L,R}}\tau_a}\varphi_{\mathrm{L,R}} \,,$$

τ_a generators of $\mathrm{SU}(N_f)$

vector (V) and axial-vector (A) transformations for $\Theta^a_{\mathrm{R}} = \pm\Theta^a_{\mathrm{L}} = \Theta^a$

V: $\varphi \longrightarrow e^{-i\Theta^a\tau_a}\varphi$ A: $\varphi \longrightarrow e^{-i\Theta^a\tau_a\gamma_5}\varphi$

example chiral condensate

$$\langle\bar\varphi\varphi\rangle = \langle\bar\varphi_{\mathrm{L}}\varphi_{\mathrm{R}}\rangle + \langle\bar\varphi_{\mathrm{R}}\varphi_{\mathrm{L}}\rangle \longrightarrow \langle\bar\varphi_{\mathrm{L}} e^{-i(\Theta^a_{\mathrm{R}}-\Theta^a_{\mathrm{L}})\tau_a}\varphi_{\mathrm{R}}\rangle + (\mathrm{L} \longleftrightarrow \mathrm{R})$$

Chirally Odd Condensates in Weinberg Sum Rules

Example: ρ meson

$$\varphi = \begin{pmatrix} u \\ d \end{pmatrix}$$

chiral transformations

Pauli metrices

$$\varphi_{\mathrm{L,R}} \longrightarrow e^{-i\Theta^a_{\mathrm{L,R}}\tau_a}\varphi_{\mathrm{L,R}}\,, \qquad \tau_a = \sigma_a/2$$

$$\langle\bar{q}q\bar{q}q\rangle_{\mathrm{odd}} = \langle(\bar{\varphi}_{\mathrm{R}}\gamma_\mu\lambda^A\tau_3\varphi_{\mathrm{R}})(\bar{\varphi}_{\mathrm{L}}\gamma^\mu\lambda^A\tau_3\varphi_{\mathrm{L}})\rangle$$

[Hilger et al., PLB 709 (2012)]

Weinberg Sum Rules of ρ and a_1 – degenerating spectral functions

$$\int ds\,\frac{1}{s}\Delta\rho(s) = f_\pi^2$$

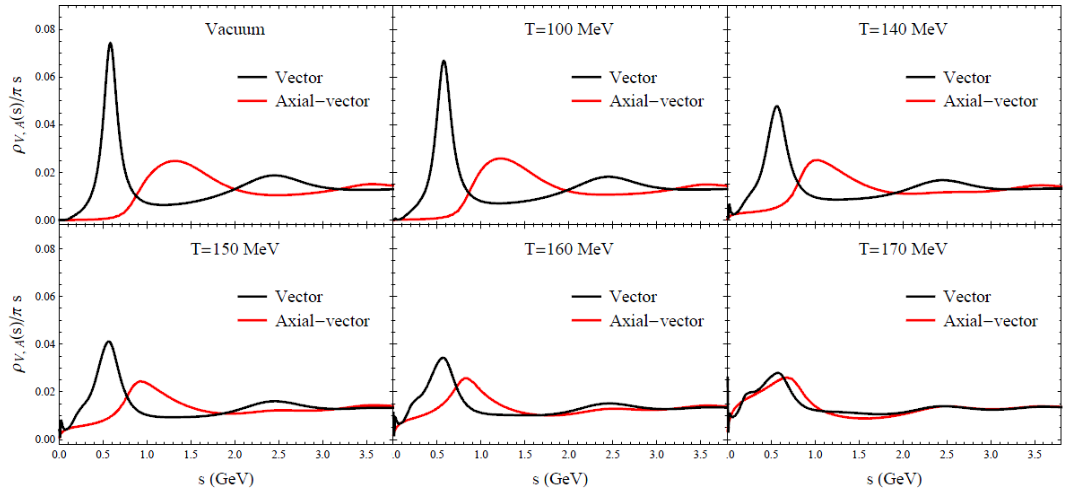
$$\int ds\,\Delta\rho(s) = 0$$

$$\int ds\,s\Delta\rho(s) = -2\pi\alpha_s\langle\bar{q}q\bar{q}q\rangle_{\mathrm{odd}}$$

with $\Delta\rho = \rho_{\mathrm{V}} - \rho_{\mathrm{A}}$

microscopic calculation (had. eff. field theory)

with parameters from minimization of inequalities in the WSR



[Hohler, Rapp, PLB 731 (2014)]

Translation to Open Charm Mesons

[Hilger et al., PRC 84 (2011)]

$\varphi = \begin{pmatrix} u \\ d \\ Q \end{pmatrix}$ with chiral transformations restricted to *light* part

➔ leaves QCD Lagrangian invariant, especially $\bar{\varphi} M \varphi \, , M = \mathrm{diag}(0, 0, m_Q)$

chiral partner meson currents transform into each other

⚠

observed splitting of chiral partner spectra

D meson: $\frac{m_P}{m_S} \sim \frac{1800}{2300} \, , \frac{m_V}{m_A} \sim \frac{2000}{2400}$

➔ spontaneous symmetry breaking, driven by order parameters,

e.g. $\langle \bar{q} q \rangle$, $\langle \bar{q} q \bar{q} q \rangle_{\mathrm{odd}}$

✔ translation complete

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Chiral Partner Mesons with Open Charm

Weinberg-type sum rules for open charm mesons

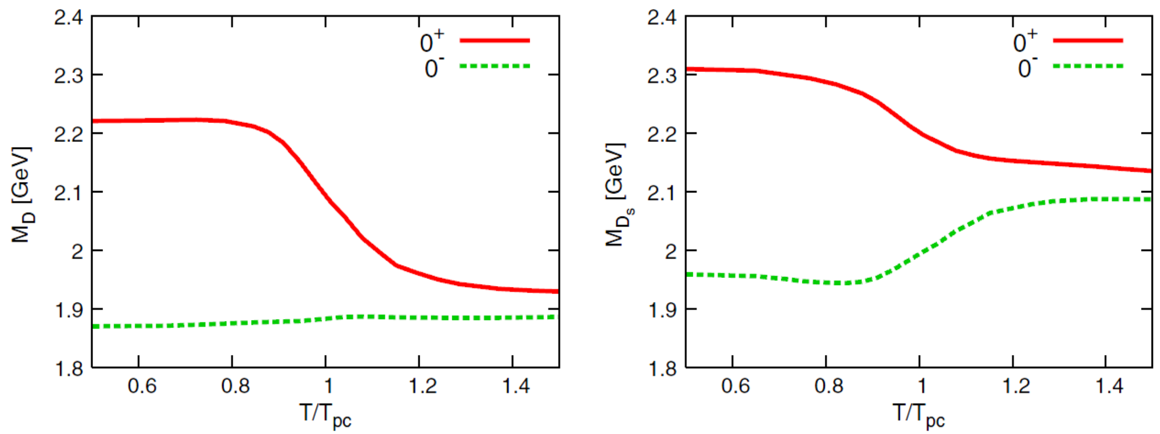
- up to condensates of mass dimension 5 for P/S and V/A in [Hilger et al., PRC 84 (2011)]

- extension to mass dimension 6 ➜ identified for P/S:

$$\langle \bar{q}q\bar{q}q \rangle_{\mathrm{odd}} = \langle (\bar{\varphi}_{\mathrm{R}} \lambda^A \varphi_{\mathrm{L}})(\bar{\varphi}_{\mathrm{L}} \not{v} \lambda^A \varphi_{\mathrm{L}}) \rangle + \langle (\bar{\varphi}_{\mathrm{L}} \lambda^A \varphi_{\mathrm{R}})(\bar{\varphi}_{\mathrm{L}} \not{v} \lambda^A \varphi_{\mathrm{L}}) \rangle + (\mathrm{L} \longleftrightarrow \mathrm{R})$$

[Buchheim et al., PRC 91 (2015)]

Check hadronic models for D mesons



[Sasaki, PRD 90 (2014)]

Summary

- QCD sum rules link order parameters of chiral symmetry breaking, e.g. $\langle \bar{q} q \rangle$, to hadron properties (moments of spectral density)
- D meson is excellent probe of hot/dense nuclear matter, its sum rule is more sensitive to the chiral condensate than light meson (ρ, ω) sum rules
- vanishing (diminished) chirally odd condensates, e.g. $\langle \bar{q} q \rangle$ and $\langle \bar{q} q \bar{q} q \rangle_{\mathrm{odd}}$ lead to degeneracy (approaching) chiral partner spectra, quantified in Weinberg sum rules V-A and P-S

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